

# Prospective CO<sub>2</sub> emissions from energy supplying systems: photovoltaic systems and conventional grid within Spanish frame conditions

Antonio Dominguez-Ramos · Michael Held ·  
Ruben Aldaco · Matthias Fischer · Angel Irabien

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## Abstract

*Background, aim, and scope* In order to assess the environmental sustainability of a novel wastewater treatment process based on power an electrochemical reactor by photovoltaic solar modules (photovoltaic solar electrochemical oxidation), a life cycle approach was considered to quantify the CO<sub>2</sub> equivalent (CO<sub>2</sub>-eq.) emissions coming from the two supplying power systems to the electrochemical process: conventional grid power or photovoltaic solar power under Spain frame conditions.

*Materials and methods* GaBi 4 software was used to build models to characterize the conventional grid and photovoltaic power generation (corresponding functional unit, 1 kWh). ecoinvent v2.0 was chosen to consider background data. Nine different 2030 scenarios were evaluated versus

2007 reference values to take into account: (a) the progressive change to a greener grid mix in Spain and (b) the improvements in photovoltaic solar technology.

*Results* The results showed that, under the nine considered scenarios for 2030, the CO<sub>2</sub>-eq.per kilowatt hour emissions are always lower than the reference values for 2007 (reductions around 60%). Additionally, the results showed that 2030 values for the CO<sub>2</sub>-eq.per kilowatt hour emissions coming from the use of photovoltaic modules for power generation are expected to be around 60% lower than for 2007 values.

*Discussion* In order to power an electrochemical process, the direct use of photovoltaic solar energy will give much lower CO<sub>2</sub>-eq.per kilowatt hour emissions than the supply from conventional grid.

*Conclusions* A quantitative study based on life cycle assessment has compared the CO<sub>2</sub>-eq.per kilowatt hour emissions coming from supplying an electrochemical reactor by conventional grid and by photovoltaic solar modules under Spanish frame conditions and stated that the novel process photovoltaic solar electrochemical oxidation would be a preferred environmental option due to the lower CO<sub>2</sub>-eq.per kilowatt hour emissions under present and future scenarios.

*Recommendations and perspectives* The results would suggest that it is worthy to explore not only the possibilities of this technology but also other electrochemical technologies that can be supplied directly by electricity in order to have a better sustainability performance.

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A. Dominguez-Ramos (✉) · R. Aldaco · A. Irabien  
Department of Chemical Engineering and Inorganic Chemistry,  
University of Cantabria,  
Avda. Los Castros,  
39005 Santander, Spain  
e-mail: dominguez@unican.es

M. Held  
Abteilung Ganzheitliche Bilanzierung, LBP,  
University of Stuttgart,  
Hauptstrasse 113,  
70771 Echterdingen, Germany

M. Fischer  
Department of Life Cycle Engineering,  
Fraunhofer Institute for Building Physics,  
Hauptstrasse 113,  
70771 Echterdingen, Germany

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## 1 Background, aim, and scope

### 1.1 Background

Within the current energy global framework, the integration of renewable energy sources into production systems is a key point to be challenged as mentioned in “A roadmap for the 21th century chemical engineering” of the Institution of Chemical Engineers (IChemE 2007). Thus, being energy one of the main actors of the process sustainability, the progressive phasing out of fossil fuels ought to be a basic step in the overall transition to a cleaner primary energy. State-of-the-art technology for wastewater treatment makes it possible to transform water scarcity into diverse energy-intensive scenarios.

Technologies such as electrochemical oxidation (EO) supporting boron-doped diamond (BDD) electrodes has been claimed as a promising technology not only in purification and disinfection applications but also for depuration and therefore promoting water reclamation and reduced net usage of water from original sources. This technology has been successfully applied for different polluted industrial wastewaters such as olive mill, pulp and paper, textile, pharmaceutical, landfill leachate, leather, phenol formaldehyde, oil refinery, bulk drug manufacture, carwash, and motor industry (Dominguez-Ramos et al. 2008). From an operating point of view, EO has been emphasized as a suitable technology in those cases in which the chemical oxygen demand is below 5,000 mgO<sub>2</sub>l<sup>-1</sup>, although a wide range of applications ranging from 100,000 to 1,000 mgO<sub>2</sub>l<sup>-1</sup> has been suggested. In the comparison with other advanced oxidation processes, the sludge and consumption of chemicals reduction are very attractive features of electrochemical oxidation from a life cycle (LC) perspective. BDD has been widely recognized as an excellent material for electrodes to perform electrochemical oxidation for the removal of organics from wastewater due to its high anodic stability and wide potential window. Derived from the unique surface properties, BDD electrodes can perform the electrocombustion of the organic matter with energetic efficiency under the appropriate operational conditions. When applying an electrical current to the electrodes, powerful oxidants can be created at the surface or in the bulk liquid phase, depending on the operational conditions and therefore promoting the combustion of the organic matter to CO<sub>2</sub> and H<sub>2</sub>O. Nevertheless, this technology lacks attractiveness due to the electrical energy consumption per unit of volume treated (Cañizares et al. 2002), which is a major drawback due to the contribution to global warming as well as other environmental impacts. Life cycle approach shows the shift of burdens between life cycle phases or processes when EO is based on grid power to get high-quality water. In order to

overcome the previously described situation, the integration of photovoltaic solar systems as primary energy source to the EO process was proposed as only electricity as direct current is required. The result is a photovoltaic solar powered electrochemical oxidation (PSEO) process (Dominguez-Ramos et al. 2010), in which electrons collected by the solar modules are used directly to generate powerful oxidants into the liquid phase of the polluted effluent, which remove organic matter up to the desired values. This option annuls the need of massive energy storage systems in the form of lead–sulfuric acid batteries, which is typical for photovoltaic systems or other energy storage systems such as Li-ion batteries. Specially for continuous treatment, an appropriate design of raw water tanks will allow the process to accumulate the contaminated effluent and to be working under low or null irradiation periods (e.g., night, overcast conditions, winter, etc.). The integration of photovoltaic solar systems is expected to be an adequate solution for a Mediterranean country such as Spain, with very good perspectives for PV technology issues, not only manufacturing and R&D but also for power generation (Salas and Olias 2008). If water scarcity is added to that previous statement, PSEO processes are likely to be interesting in the mid-term considering water reuse and reclamation objectives.

### 1.2 Aim and scope of the work

The aim of this work is to obtain a quantitative estimation of the environmental benefits in terms of CO<sub>2</sub> equivalent (CO<sub>2</sub>-eq.) emissions of using photovoltaic solar electricity for the self-sustainable PSEO processes instead of conventional grid power by means of LC Assessment (LCA) methodology (ISO 2006a, b). Therefore, an assessment of the quantity of GHG emissions expressed as kilograms of CO<sub>2</sub>-eq. from grid power and current commercial PV modules in 2007 was performed, being Spain the chosen country for frame conditions such as solar irradiation, performance ratio of the PV modules, country grid mix, etc. Furthermore, a prospective analysis expressed as kilograms of CO<sub>2</sub>-eq. emissions for 2030 from the future PV modules and grid power in Spain was also carried out to have a quantitative estimation of the benefits in carbon footprint terms that PSEO takes from using solar photovoltaic energy.

To describe the grid power generation, only the representative reported technologies contributing to the power grid mix in Spain were considered. Those technologies with an expected minority contribution (such as residual heat or solar thermoelectric) were out of the scope of this work. As many PV technologies are now available for electricity supply, only those that have representative prospective studies were considered in this work. Although

other technologies like dye-sensitized or organic polymer solar cells seem to be occupying a notable share of the market in the future, they were not analyzed as the prospective studies for them are not suitable for the present work. The boundary limits of the modeled systems are shown in Fig. 1.

## 2 Materials and methods

The models described in this work to characterize the behavior of the power grid mix and the photovoltaic system performance were built using GaBi 4 LCA software (GaBi 2008). For the upstream processes, ecoinvent v2.0 (ecoinvent 2008) as background data was used. The collections of data for the grid mix and PV performance in 2007 and 2030 were collected from various studies being given extra details later. Unless the opposite is stated, all unit process data come from ecoinvent v2.0, and the different parameters used along the text are only valid for the models developed for the grid mix and the photovoltaic systems.

In order to build the model discussed later for power grid mix generation, different technologies available in ecoinvent 2.0 were utilized to complete the best possible matching with the description of considered technologies in the different references for the grid mix (see Table 1 for selected technologies). A model taking into account the energy balance in the whole grid was used to assess imports, exports, own consumption, and water pumping. Net losses were modeled as background data (it is estimated that 1.025 kWh is required from the grid to get 1 kWh at medium voltage). Therefore, consistency, representativeness, and reliability are guaranteed as the minimum number of modifications (with respect to the models in ecoinvent v2.0) was performed to complete the description of the grid mix and later power distribution. For PV power, a model

was used to calculate the output energy from a PV module in its lifetime considering solar irradiation, performance ratio, efficiency, and lifetime.

## 3 Description of evaluated energy systems

The grid power from Spain at medium voltage and the power from different PV technologies have been considered to supply the PSEO process. Between the PV technologies, the wafer silicon-based PV technologies (multicrystalline silicon (mc-Si) and monocrystalline silicon (c-Si)), the silicon ribbon technology (Ribbon-Si), and the thin film technologies (amorphous silicon (a-Si), cadmium telluride (CdTe), and copper–indium–gallium–sulfur–selenide (CIGS)) were considered as alternatives.

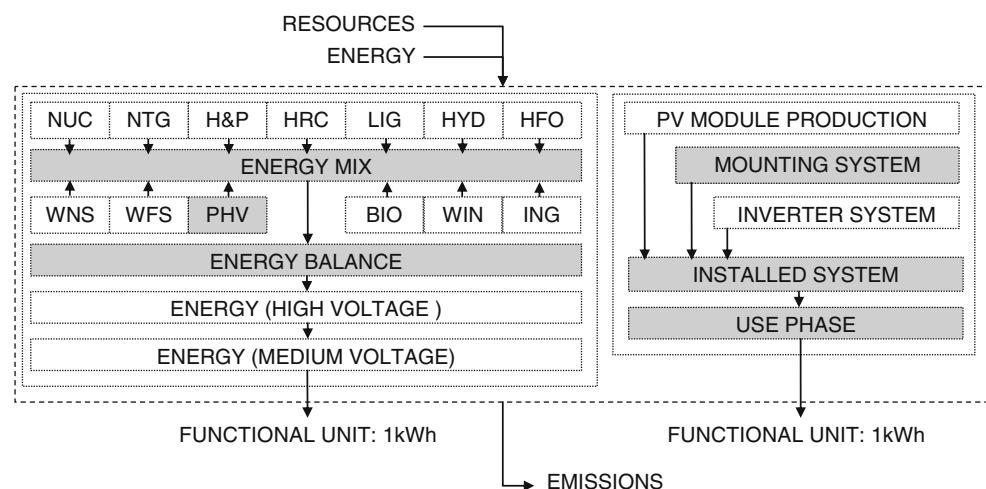
### 3.1 Description of the modeled energy systems

#### 3.1.1 Modeled grid power

The grid power system was structured in three steps. In the first step, the grid mix was modeled considering the contribution of the different power plants existing in Spain and data availability from ecoinvent (2008). The grid mix for Spain in 2007 is summarized in Table 1.

For consistency purposes and because of certain lack of reliable data and in order to match the share of the technologies from the former reference, residual heat and solar thermoelectric were excluded from this study (this assumption would be reasonable as its expected contribution is less than 1%). On the other hand, it was estimated that 85% of imported coal is hard coal for combustion purposes. For electricity generation from natural gas, ecoinvent v2.0 typically considers combustion in gas burners. However, natural gas is mainly combusted using

**Fig. 1** System boundary of the modeled energy systems (*left* grid power generation and *right* solar photovoltaic generation). Modules using foreground data are *highlighted*



**Table 1** Shares of technologies for power generation in the Spanish grid mix in 2007 and 2030 (under the nine considered scenarios)

Technology	Ref. 2007	MUS-NGP	NE-NGP	MPW-NGP	CC-NE-NGP	MUS-CP	NE-CP	MPW-CP	CC-CP	CC-NE-CP
Nuclear	18.6	14.1	24.6	14.0	18.3	14.1	24.6	14.0	14.1	18.3
Natural gas	24.4	42.3	32.0	26.4	34.4	41.6	31.1	25.5	31.0	31.1
Heat and power	5.7	6.3	6.3	6.2	6.3	6.3	6.3	6.2	6.3	6.3
Hard coal	20.7	0.2	0.1	0.0	4.0	1.0	0.9	0.9	11.5	7.3
Lignite	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hydro	10.3	9.2	9.2	10.0	9.2	9.2	9.2	10.0	9.2	9.2
Heavy fuel oil	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind on shore	9.1	20.8	20.8	29.7	20.8	20.8	20.8	29.7	20.8	20.8
Wind off shore	0.0	3.5	3.5	10.2	3.5	3.5	3.5	10.2	3.5	3.5
Photovoltaic	0.2	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Biomass	0.8	1.6	1.6	1.5	1.6	1.6	1.6	1.5	1.6	1.6
Waste Inc	0.8	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Industrial gas	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Values expressed as percentage

combined cycle stations in Spain; therefore, it was assumed as reference that 100% of the natural gas is combusted in combined cycle stations (in ecoinvent v2.0, the generation of 1 kWh releases 0.425 versus 0.515 kg CO<sub>2</sub>-eq. when combined cycle is selected). Combined cycle stations were assumed for 2030 scenarios.

For those scenarios in which coal stations and carbon capture and storage (CCS) are considered, the emissions from the life cycle of an integrated gasification combined cycle (IGCC) equipped with CCS (precombustion physical absorption with Selexol solvent) from Odeh and Cockerill (2008) was used (this is the only unit process whose emissions inventory does not come from ecoinvent v2.0). For hydropower plants, 85% of the total power was assumed to come from run-of-river plants and 15% from reservoir plants (SGE 2008). Furthermore, it was estimated that the photovoltaic contribution to power generation was based on ground-mounted installations and modeled as discussed later. Table 2 summarizes the global market shares of PV technologies that were used to consider the PV contribution to the grid power in 2007 and 2030 (EPIA and Greenpeace 2008; EPIA 2008), being remarkable that the wafer silicon-based technology is about 90% of the

market in 2007 and that in 2030 this value is reduced to around 35%. For 2030, a 35% of the share is assigned to conventional silicon technology, a 30% to thin-film technology, and a 35% to new developments such as organic cells. To simplify the current analysis, the contribution of new developments was skipped, keeping the proportions given by the 2007 shares. On the other hand, the share of energy corresponding to meet peak power demand in 2030 was assumed to be based on natural gas (UNESA 2007) and therefore included in the share shown in Table 1. In the second step, an energy balance considering imports, exports, owned consumed, and water pumping energy was completed as second level as summarized in Eq. 1:

$$E_{\text{Gen}} = E_M + E_{\text{Imp}} - E_{\text{Exp}} - E_{\text{Pum}} - E_{\text{OC}} \quad (1)$$

where the  $E_{\text{Gen}}$  stands for the available energy for distribution,  $E_M$  is the energy given by the set of considered technologies to the grid mix (the contribution in energy units of each technology to the mix can be obtained considering the shares shown in Table 1 and the total energy from the grid mix  $E_M$  shown in Table 3),  $E_{\text{Imp}}$  is the mix of the imported energy (82% and 18% from France and Portugal grid mix, respectively, using ecoinvent v2.0

**Table 2** Shares of PV technologies used for prospected scenarios in 2007 and 2030

	a-Si	CdTe	CIGS	mc-Si	c-Si	Ribbon-Si
2007	5.2	4.7	0.5	45.2	42.2	2.2
2030	35	10	1	27	25	1

Values expressed as percentage

**Table 3** Contribution of each energy term to the total energy generation  $E_{\text{Gen}}$  in 2007

$E_M$	$E_{\text{Imp}}$	$E_{\text{Exp}}$	$E_{\text{Pum}}$	$E_{\text{OC}}$	$E_{\text{Gen}}$
296,552	8,874	14,630	4,349	9,600	276,847

Values expressed as gigawatt hours

references for the grid mix data),  $E_{\text{Exp}}$  is the exported energy,  $E_{\text{Pum}}$  is the energy used for water pumping, and  $E_{\text{OC}}$  is the energy used as own consumption in the generation of the energy. Table 3 shows the values used for the energy balance in 2007. For the 2030 scenarios,  $E_{\text{Imp}}$  and  $E_{\text{Exp}}$  were not considered as there is not any reliable forecast for the interchange of power between Spain and neighbor countries,  $E_{\text{Pum}}$  were assumed proportional to the energy obtained by hydropower, and  $E_{\text{OC}}$  was also proportional but to the total energy required. Finally, in the third step, the net distribution losses at high and medium voltage are considered using the ecoinvent v2.0 structure (ecoinvent 2008). The losses ratio of the available energy to the distributed energy at medium voltage was around 2.5% as previously cited and was used for both 2007 and 2030 scenarios.

### 3.1.2 Modeled PV energy systems

Pacca et al. (2007) stated that there are four main factors affecting the environmental performance of PV modules: solar irradiation, efficiency (conversion of sunlight), lifetime and energy consumption, and fuel mix employed in the manufacturing process. For the PV systems, a used phase model was used to convert a set of the first three key parameters: solar irradiation, efficiency, and module lifetime plus performance ratio into energy per unit of area, as expressed in Eq. 2:

$$E_{\text{PV}} = GE_f LT_{\text{PV}} PR \quad (2)$$

where  $G$  is the annual solar irradiation on a plane over the selected location,  $E_f$  is the efficiency for the solar module,  $LT_{\text{PV}}$  is the lifetime assumed for the PV module, and  $PR$  is the performance ratio (correction factor to consider deviation from ideal conditions: dust, shadowing effects, etc.). In Eq. 2, it is assumed that energy production is based on the irradiation on a plane, and a degradation rate of 0.5% per year was used to annualize the total power given the module in its corresponding lifetime. The fuel mix employed was based on the background data taken from (ecoinvent 2008). The number of inverters of 500 kW<sub>p</sub> required for each installed kW<sub>p</sub> of PV module is directly

proportional to the module efficiency and the ratio of the lifetimes of the PV modules and the inverters. Due to the wide range of ground mounting systems available in the market, 5 kg of steel and 2 kg of PVC per 1 m<sup>2</sup> of module area were used, being these data compatible with (Mason et al. 2006). No environmental credits are obtained from metal parts or silicon recycling after PV modules dismantling (Jungbluth 2005; ecoinvent 2008).

The models for the different PV modules production were taken from (ecoinvent 2008). The values of the PV parameters for 2007 for Spain were adopted among several sources (ASIF 2008; EPIA and Greenpeace 2008; Pfatischer 2008) and summarized in Table 4. A ground-mounted configuration with framed modules (except for CdTe) was adopted for the six PV technologies, and a mean annual irradiation in plane for Spain of 1,825 kWh(m<sup>2</sup>year)<sup>-1</sup> was assumed: A weighted mean value was calculated considering the share of each autonomous communities in Spain for 2007 to PV power generation (ASIF 2008) and the irradiation over each community (PVGIS 2008). PV production data for c-Si modules come from 2004 (except 2005 for Siemens polysilicon and 2002 for metallurgical grade silicon); the production of c-Si by means of the Czochralski silicon ingots and later wafer sawing, cell, and module production processes are supplied by UCTE electricity using 2004 data. For CdTe, data are from 2006 (using the German grid mix for 2004) and for CIGS from 2007 (using also the German grid mix for 2004).

## 3.2 Description of the prospected scenarios

### 3.2.1 Power grid mix scenarios

The main content of UNESA's Outlook for Electricity Generation for 2030 (UNESA 2007) report is the assessment of the future electric generation mix in Spain based on the established objectives for the planning of the generation, the objectives of the European and Spanish energy policy, and the possible evolution of the Spanish power generation stations under different scenarios. This report was externally reviewed by the Electric Power Research

**Table 4** Main PV parameters in 2007 and 2030

	2007				2030			
	$E_f$	PR	$LT_{\text{PV}}$	$LT_{\text{INV}}$	$E_f$	PR	$LT_{\text{PV}}$	$LT_{\text{INV}}$
Values of module efficiency and performance ratio expressed as percentage. Values of lifetime of modules and inverters expressed as years								
c-Si	15	78	30	20	25	83	35	30
mc-Si	13	78	30	20	25	83	35	30
Ribbon-Si	12	78	30	20	20	83	35	30
a-Si	7	78	30	20	15	83	30	30
CIGS	10	78	30	20	15	83	30	30
CdTe	9	78	30	20	15	83	30	30

$E_f$  module efficiency,  $PR$  performance ratio,  $LT_{\text{PV}}$  PV module lifetime,  $LT_{\text{INV}}$  inverter lifetime

Institute, which confirmed the technical assumptions and hypotheses presented by UNESA. Therefore, the different envisaged scenarios guarantee the reliability of the present work. The methodology to build the different scenarios consider the future power demand, the current installed stations, the confirmed and planned connection of new stations to the grid up to 2013, the phase out of old stations, and the stations to produce renewable energy under the plan of renewable energies in Spain (IDAE 2005). More details can be found in UNESA (2007). These scenarios to meet the future energy demand in Spain are now summarized:

1. Maximum usage of current stations (MUS): The extra power demand is supplied by the planned stations for 2013. Base load and peak power demand are supplied essentially by natural gas
2. Nuclear expansion (NE): A strong expansion of the nuclear share is envisaged to meet the base load demand. Natural gas is used for peak power demand
3. Maximum penetration of wind power (MPW): High penetration of renewable energies (specially wind power) to help base load and peak power demand
4. Carbon capture (CC): Coal keeps a relative important share in the grid mix. Hard coal power plants are equipped with CCS stations
5. Carbon capture combined with nuclear expansion (CC-NE): Coal combustion equipped with CCS stations and nuclear energy are combined to supply the base load demand

Because of the uncertainty in the preferred fossil fuel in the future due to fluctuations in the prices of CO<sub>2</sub> in the emission trade market and prices of raw fuels, two different assumptions were considered: natural gas as preferred fuel (NGP) and coal as preferred (CP) which led to nine different scenarios (the CC scenario is not considered within the NGP assumption). The 2007 and 2030 scenarios shares of technologies for power generation are summarized in Table 1. The total electric energy at grid  $E_M$  for 2007 was 297 TWh (REE 2008). From UNESA (2007), a total of 428 TWh will be required to meet the electricity demand in 2030. From Table 1, it is noticeable that all of envisaged scenarios expect to reduce the CO<sub>2</sub>-eq. emissions from current levels to meet the Kyoto's Protocol objectives for Spain: This fact is clearly shown in the phase out of hard coal, lignite, and fuel oil plants and the commitment with renewable energies. As there are no estimates about the future exchanges with neighboring countries, the self-sufficiency is assumed for Spain as a first step.

### 3.2.2 PV power scenario

A set of parameters related to PV modules for 2030 from several data sources (Frankl et al. 2005; NREL 2007a, b,

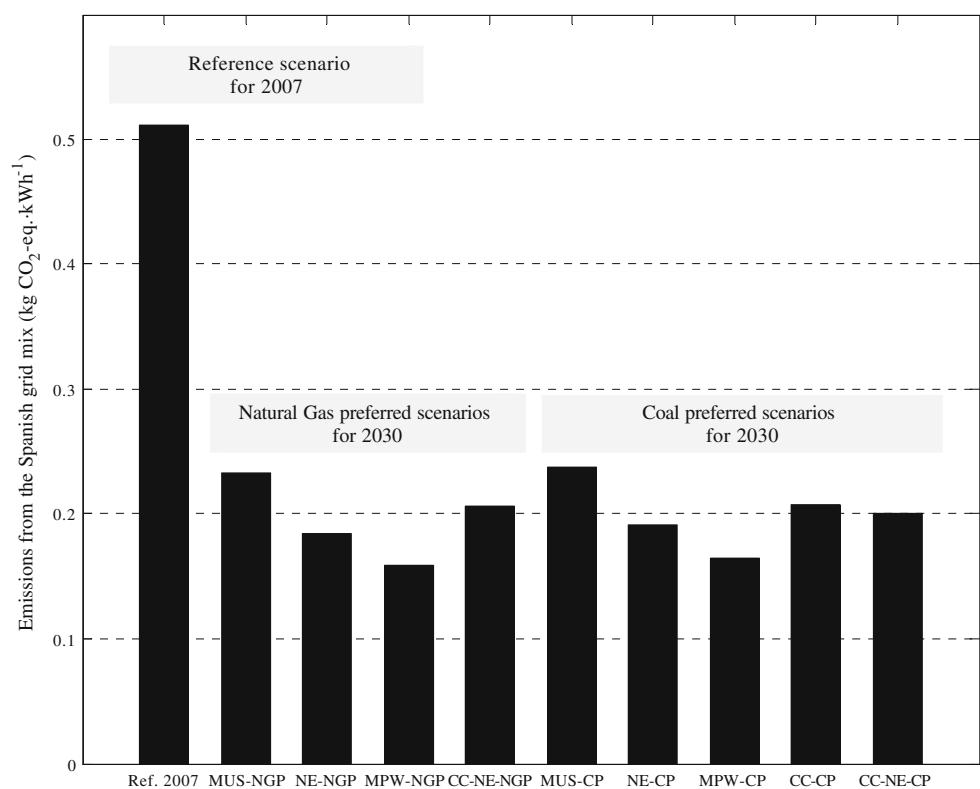
c, d; Morales-Acevedo 2006; EUPVTP 2007; Raugei and Frankl 2009) are included in Table 4, considering all those parameters used in Eq. 2 for  $E_{PV}$ . In order to quantify future improvements in manufacturing processes of PV modules, a general reduction of 20% in materials and energy required per 1 m<sup>2</sup> of module area was applied (Frankl et al. 2005). No modification of annual irradiation is considered.

## 4 Results and discussion

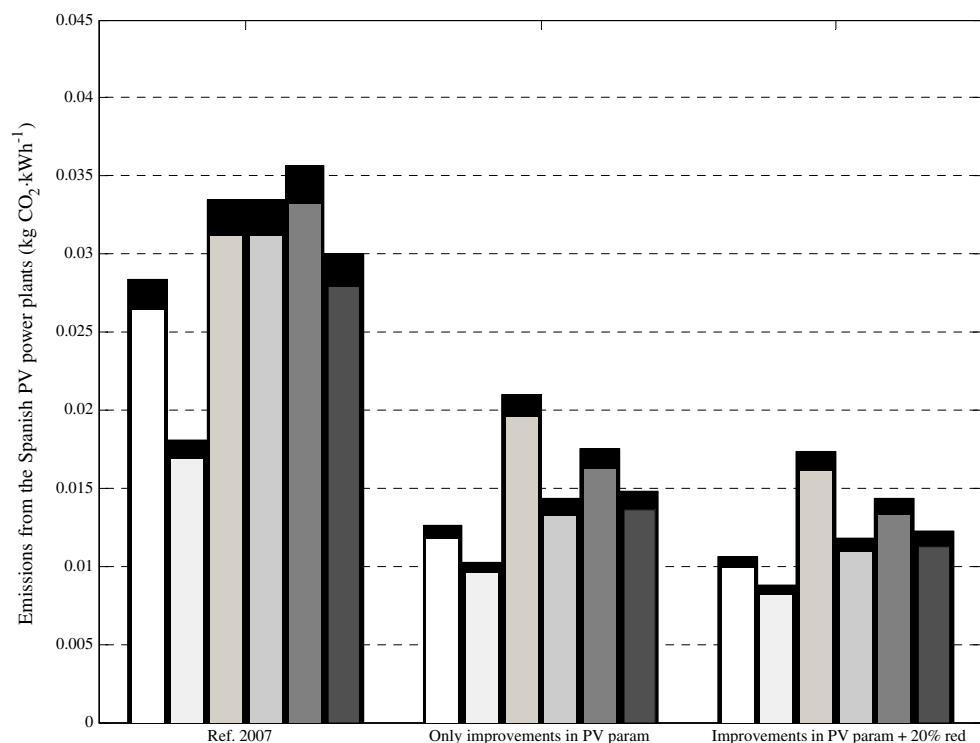
GaBi 4 software (GaBi 2008) was used to build a LCA model and quantify the CO<sub>2</sub>-eq. emissions for all energy systems when supplying the energy required by the PSEO process. These CO<sub>2</sub>-eq. emissions were assessed using the global warming equivalence factors proposed in the CML2001 methodology (implemented in GaBi 4), which are based on the IPCC equivalence factors for 100 years (with updated factors for 2007). The 2007 updated available data for the Spanish grid mix is reported in Table 1 and used to assess the current CO<sub>2</sub>-eq. emissions (REE 2008). From Fig. 2, in Spain 2007, 0.511 kg CO<sub>2</sub>-eq. kWh<sup>-1</sup> at medium voltage was released in the life cycle considering all the previous hypotheses for Spain in the year 2007. This value is about 14% higher than the direct emissions reported for electricity production in the same period (0.450 kg CO<sub>2</sub> kWh<sup>-1</sup>; SGE 2008), which really fits the percentage of life cycle emissions over direct emissions typically considered around 10–15% higher.

On the other hand, the nine considered scenarios proposed reductions in the CO<sub>2</sub>-eq. emissions, which range from 53% to 69% versus 2007 values. This improvement is based in the progressive substitution of hard coal, lignite, and fuel oil power plants for natural gas and wind power plants. Of course, the lowest values from Fig. 2 (0.159 and 0.165 kg CO<sub>2</sub>-eq. kWh<sup>-1</sup>) were obtained for the scenarios MPW-NGP and MPW-CP, in which the energy demand is met by an important contribution of renewable energies, specially wind power (total share of 40%), being natural gas used for both the baseline and peak demand. Values up to 0.208 and 0.201 kg CO<sub>2</sub>-eq. kWh<sup>-1</sup> were obtained, respectively, for CC-CP and CC-NE-CP scenarios as shown in Fig. 3, which are those whose share of hard coal to the grid mix remain relevant (11% and 7%, respectively, compared with the 21% in 2007). Assuming the same probability for each scenario, a mean reduction of 62% is expected for all the NGP scenarios and of 61% for the CP scenarios. Therefore, significant reductions are expected to happen in Spain for CO<sub>2</sub>-eq. emissions coming from the power generation sector under conditions assumed in this work and based on currently available references.

**Fig. 2** Emissions from the Spanish grid mix for the 2007 and 2030 scenarios. Values expressed as kilograms of  $\text{CO}_2\text{-eq.}\cdot\text{per kilowatt hour}$



**Fig. 3** Emissions from the Spanish PV power plants for the 2007 and 2030 scenarios. Values expressed as kilograms of  $\text{CO}_2\text{-eq.}\cdot\text{per kilowatt hour}$ . Colored bars represent values without degradation, and the corresponding black bar represents the value assuming a degradation rate of 0.5% per year: □ a-Si, □ CdTe, □ CIGS, □ mc-Si, □ c-Si, □ Ribbon-Si



As the power generation is due to two main technologies, wind power and natural gas, four main hypotheses had to be assumed:

1. Improvements performed in the manufacturing process of wind power stations are not considered. Consequently, environmental improvements related to a greener grid power for a more sustainable manufacturing process were not computed.
2. The emission factors of combined cycle stations and natural gas burners are critical for the study. A prospective study for those technologies is not considered, so it must be highlighted that lower emission factors (as previously cited 0.425 kg CO<sub>2</sub>kWh<sup>-1</sup> for best combined cycle and 0.515 kg CO<sub>2</sub>kWh<sup>-1</sup> for natural gas burners (ecoinvent 2008)) could be expected and consequently lower CO<sub>2</sub>-eq. emissions could arise.
3. No CCS stations are incorporated together with natural gas combined cycles or cogeneration. This is due to the fact that the original reference for prospected scenarios (SGE 2008) reports that CCS stations are only integrated in coal stations. Weisser (2007) reviewed emissions from CCS stations, reporting values between 0.092–0.145 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for pulverized coal plants, 0.065–0.152 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for IGCC plants, and 0.040–0.066 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for combined cycle gas turbine plants. Viebahn et al. (2007) reported values below 0.200 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for pulverized hard coal, pulverized lignite, NGCC, and IGCC technologies equipped with CCS (reaching around 0.150 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> in IGCC plants with CCS). Odeh and Cockerill (2008) reviewed different life cycle analysis of power generation stations with CCS and reported values below 0.250 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> from several authors, pointing out that reductions up to 0.160 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> were possible depending upon the chosen technology. Pehnt and Henkel (2009) also reported values below 0.200 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for an IGCC station equipped with CCS, based on Selexol and without considering CO<sub>2</sub> leakages (this reference was used for the inventory). Consequently, it is expected that, if more demanding measures are considered in a close future, it is reasonable to consider a greater penetration of CCS stations also in NGCC plants, so the expected emissions could be even lower than those reported previously.
4. Dynamic criteria in the background data are not considered. Pehnt (2006) suggested that different estimations can be done for critical parameters affecting the life cycle performance of a system product so it is possible to forecast the future impact. However, in this work, for both energy supplying systems, it was

considered that future scenarios for grid power and PV systems rely on the most updated data from (ecoinvent 2008) in the upstream processes, which is analogous to consider that the power generation in 2030 is based on emissions factors and efficiencies of 2004 and that the PV systems are produced with 2004 energy and materials (date of inventory data on ecoinvent v2.0 database). That leads to the fact that a worst case scenario is assumed and the expected environmental performance should be better than concluded here.

Additionally, it seems logical that those values could be also lower if it is considered that renewable energies such as solar thermoelectric are not considered. Therefore, values presented here for the CO<sub>2</sub>-eq. emissions must be interpreted as a worst case situation as all the presented hypotheses lead to improvements in the environmental performance of both power generation from grid and from PV power plants: An improvement in all upstream processes is of course expected taking into account current global environmental status and legislation.

Results for PV power plants in Spain are reported in Fig. 3. Values between 0.026 and 0.033 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> were obtained for the different PV technologies (except CdTe due to the less energy-intensive production process and frameless assumption). For the wafer silicon-based, silicon ribbon, and CdTe technologies, proposed values agree with those reported by Fthenakis et al. (2008), as both studies used ecoinvent as background data. Values between 0.052 and 0.072 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> were obtained for crystalline modules by Raugei et al. (2007b). These authors report values of 0.017 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for frameless CdTe technology: Divergence in reported values is possible as it depends on the different assumptions made in the goal and scope definition step (also different assumptions could lead to similar final values). For very large-scale PV systems, Ito et al. (2008) reported values of 0.0121, 0.0094, 0.0156, 0.0128, and 0.0105 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> for typical efficiency mc-Si, high efficiency mc-Si, a-Si, CdTe, and CIGS modules, respectively: These values are half those presented in Fig. 3, which means that operating under high irradiation in very large-scale systems reduces the value of the environmental performance expressed as kilograms of CO<sub>2</sub>-eq.per kilowatt hour. As the PSEO process does not need the use of inverters, previous values shown in Fig. 3 were also assessed assuming no inverters in order to obtain 1 kWh and reductions in the order of 2–3.5% were obtained when the inverter were removed.

The future CO<sub>2</sub>-eq. emissions from selected technologies in 2030 considered two separated steps for a better comprehension of results. In the first step, only the improvements from the set of PV parameters in Table 4

affecting energy performance  $E_{PV}$  were considered. These reductions are in the range of 35–60%, which is reasonable as the set of future PV parameters are only slightly higher than the current values except for efficiency, for which the values are almost twofold. When the reduction of 20% in energy and materials consumption per 1 m<sup>2</sup> of module area is also considered (second step), the reduction went up around to 50–65%. Consequently, this reduction in energy and materials may be interesting from a perspective of production costs but with a relatively low impact if compared with making twofold the efficiency of the module. Although the different assumptions are made to build the future scenarios, values in the range 0.008–0.016 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> were obtained, being not really different from others references (Raugei et al. 2007a, b; Raugei and Frankl 2009) that reported values in the same range. The effect of considering a degradation rate of 0.5% per year in the module's lifetime was also presented in Fig. 3 (black bars): The increases in the thin film PV technologies are around 7% and 9% for the wafer silicon-base and silicon ribbon PV technologies, which are due to the lower relative increase of the PV efficiencies and lifetimes of the former technologies.

Consequently, it is clear that emissions from grid power in scenarios for 2030 are at different magnitude orders, so the ratio between emissions from grid power (0.159–0.238 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup>) and from PV systems (0.008–0.016 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> with the 20% reduction and no degradation and 0.009–0.017 kg CO<sub>2</sub>-eq.kWh<sup>-1</sup> with the 20% reduction and degradation) assuming mean values for the different scenarios and PV technologies are around 17–16, respectively, so that means PSEO process should be considered as a more sustainable option when compared versus supply from grid. This statement is true when Spain is considered as frame for boundary conditions due to the annual irradiation value; however, in those countries with lower irradiation values or with a lower intensity in CO<sub>2</sub>-eq. per kilowatt hour in the grid mix (such as Norway, with a negligible contribution (Stoppato 2008)), a more detailed study must be performed.

## 5 Conclusions, recommendations, and perspectives

Providing that the aim of this work is to compare the grid power and PV power for the 2030 timeframe in terms of CO<sub>2</sub>-eq. emissions as supply for a PSEO process, it is clear from this work that, also for the most “green” grid power scenario MPW-NGP whose emissions are 13 times higher than the average value of the future PV emissions (considering 0.5% per year degradation and 20% reduction in materials and energy required per 1 m<sup>2</sup> of module area), the direct use of a PV system based on any of the

considered available technologies to power PSEO process is a low-carbon intensive option. Consequently, this prospect should recognize the PSEO process, which is powered by solar photovoltaic systems, as a sound option over the supply from the grid mix. Additionally, this technological option is more energy efficient due to the fact that the energy is produced in the same place where is consumed, avoiding the consequential transmission network losses.

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